DIVISION S-7—FOREST AND RANGE SOILS

Ionic Composition of Forest Soil Solutions and Effects of Clearcutting[1]

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ABSTRACT

Soil solutions were sampled with porous-cup suction devices during a rainy season (December 1974-May 1975) from adjoining uncut and clearcut *Eucalyptus globulus* forest areas in the Berkeley hills, California. Concentrations of K^+, Ca^{2+}, Mg^{2+}, NO_3^-, HCO_3^-, and pH and specific conductance were lower in the clearcut. The high exchange capacity of the clay-loam soil, the limited amount and duration of rainfall, and the removal of slash and litter from the clearcut were factors contributing to these results which differ from those of similar studies of the effects of clearcutting elsewhere.

The relative proportions of Na^+, Cl^-, and SO_4^{2-} were higher, and those of K^+, Ca^{2+}, NO_3^-, and HCO_3^- were lower in the clearcut compared to the forest; the proportions of Mg^{2+} were the same. The relative ionic composition of soil solutions in the clearcut resembled that of the acid rain (pH 5.0). The higher proportion of HCO_3^- in the forest was due to throughfall inputs, root respiration, and decomposition of the forest floor. No NH_4^+ was detected in soil solutions from either area.

Concentrations of most ions were correlated between and within soil horizons, although K^+ was an exception due to clay fixation. During anaerobic conditions, Mn and Fe and associated Cu and Zn were mobilized in the soil solution.

Increased quantity of soil water following clearcutting resulted in increases in total amounts of most ions in solutions in the lower portion of the profile in the clearcut, compared to the uncut forest.

Additional Index Words: **nutrient concentrations, hydrology, *Eucalyptus globulus*, California, soil-water, ion transport, leaching.**

EFFECTS OF forest harvesting on water and nutrient cycling vary with tree species, time of cutting, local precipitation and temperature patterns, topography, soil characteristics, and the method of cutting and timber removal. Some of these effects have been reviewed by Sopper (1975) and Stone (1975)[3]. Unless erosion occurs, nutrient losses are usually minimal due to retention in the litter and soil, and to uptake by rapidly growing vegetation that invades the clearcut area. However, if slash is left on the ground and if revegetation is inhibited following clearcutting, large amounts of nutrients may be released to drainage waters (Likens et al., 1970). Comparison of effects of clearcutting in different locations is possible only when the factors controlling nutrient releases and movement are understood.

Ion concentrations of the soil solution were analyzed following clearcutting *Eucalyptus globulus* (Labill.) forests in the Berkeley hills, California. These forests were planted in about 1910, then clearcut in 1973-1974 following severe frost damage (Monteverdi and Wood, 1973). The soil water regime following clearcutting at this site has been reported by McColl (1977). The soil is heavy textured, rainfall occurs primarily in the winter months, and the summers are warm and dry. The conditions of this study therefore provide a comparison to similar studies in other geographical locations where different soils and climatic conditions exist (e.g., Gessel and Cole, 1965; Likens et al., 1970).

Table 1—Some characteristics of *E. globulus* forest floor and bulk density of surface soil Berkeley hills, California. *(A)* Comparison of clearcut and forest sites, *(B)* Chemical characteristics of samples from uncut forest site.

A) Characteristic	Clearcut	Forest
	Means ± standard errors	
O1 depth, cm	7.8 ± 1.1	11.1 ± 1.8 *
O2 depth, cm	10.1 ± 1.5	9.6 ± 1.4
Total depth, cm	17.9 ± 1.8	20.7 ± 2.2
% area exposed	approx. 50%	100%
Bulk density of surface soil, top 10 cm	0.84 ± 0.02	1.09 ± 0.03***

B) Chemical composition of composite O1 and O2 layers from uncut forest area (means ± standard errors).

K, %	0.20 ± 0.04
Na, %	0.50 ± 0.02
Ca, %	3.00 ± 0.22
Mg, %	0.23 ± 0.01
Cu, ppm	24.78 ± 4.12
Fe, ppm	204.33 ± 37.73
Mn, ppm	803.56 ± 133.14
Zn, ppm	55.89 ± 6.81

* Significant at the 0.05 level.
*** Significant at the 0.001 level.

SITE DESCRIPTION

The study site was located in Tilden Regional Park, Contra Costa County, California, in the hills about 2 km east of Berkeley (lat. 37°57', long, 122°15') on San Francisco Bay.

Mean annual temperature is 13.9°C, with means of 9.1°C in January and 16.4°C in July; mean annual precipitation is 56.80 cm, with means of 11.70 cm in January and 0.02 cm in July. Temperature and precipitation means are from 88-year and 30-year records, respectively. During the study period, mean monthly rainfall was 10.54 cm; the total was 118% of normal and comprised 85% of the total rainfall for the 1974-1975 wet season. Mean monthly temperature during the study period was 10.6°C, which was 0.8°C less than the normal for the same months.

The study site had a 26% slope, an easterly aspect, and an elevation of 400 m. Mean basal area of the uncut *E. globulus* forest was 48.5 m^2/ha, and mean height of dominants was 46.3 m.

The litter layer in the uncut forest had an O1 layer of loose leaves and twigs, and a more compacted O2 layer of decomposing material interspersed with fungal mycelia (Table 1).

Clearcutting at the study site was carried out in late spring 1974. Most of the slash was removed, but no burning was carried out. The original litter layer was disturbed, leaving much of the area with bared mineral soil, or with a mixture of litter and surface soil (Table 1).

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[3]E. L. Stone, 1975. Nutrient release through forest harvest: a perspective. Watershed Management Symp., Am. Soc. Civil Eng., Logan, Utah. 11–13 Aug. 1975. (Unpublished ms.).

Table 2—Ion concentration in soil solutions at various depths in clearcut and uncut *E. globulus* forest, Berkeley hills, California. Arithmetic means for samples collected during the period December 1974 to May 1975.

	Ion concentration of soil solutions, μeq/liter at various depths, cm							
	8		15		23		31	
Ion	Clearcut	Forest	Clearcut	Forest	Clearcut	Forest	Clearcut	Forest
H^+	0.6***	0.1	0.7	0.3	1.3	0.7	0.4	0.3
K^+	115.0***	355.0	81.4***	319.1	58.1***	235.3	80.2***	260.8
Na^+	325.7	375.5	431.2***	391.7	549.4*	444.4	527.3***	380.0
Ca^{2+}	746.5***	2,094.9	588.4***	1,294.9	685.3	754.7	948.8	848.4
Mg^{2+}	297.4***	668.9	274.5	463.5	327.8	372.2	385.4	367.4
NH_4^+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cu^{2+}	1.1	2.5	1.4	1.2	0.8***	1.4	1.0*	1.4
Fe^{2+}	34.8***	9.4	19.4	20.0	14.7	12.4	15.8***	6.4
Mn^{2+}	1.0	0.4	0.7	0.6	0.6	1.1	0.8	0.4
Zn^{2+}	2.6	1.7	2.7*	1.5	1.5*	2.2	2.1	1.8
Σ Cations	1,524.7	3,508.7	1,400.4	2,492.8	1,639.9	1,824.4	1,961.8	1,866.9
NO_3^-	55.4***	245.5	86.4	113.5	73.5	79.0	122.3	122.7
$H_2PO_4^-$	3.4	0.9	2.9	1.1	2.0	2.8	2.5	2.0
SO_4^{2-}	347.5	537.4	449.7	445.3	601.5**	1,033.1	395.0	402.0
Cl^-	480.0	480.0	370.0*	640.0	600.0	440.0	470.0	340.0
HCO_3^-	451.1***	1,125.0	338.4***	988.2	384.8	535.3	577.8	595.1
Σ Anions	1,337.4	2,388.8	1,247.4	2,188.1	1,661.8	2,090.2	1,567.6	1,461.8
pH	6.2***	7.0	6.2	6.5	5.8	6.2	6.4	6.5
Specific conductance μmho/cm	147 ***	341	153 ***	254	185	199	209	213

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

The soil is a fine loamy, mixed, thermic Typic Argixeroll, clay-loam developed from a basic-igneous metamorphosed-sediment complex (USDA, 1974). Particle size distribution at the study site is fairly uniform with depth, averaging 40% silt, 35% clay, and 25% sand (McColl, 1977).

Permeability is moderately slow (5-15 mm hr^{-1}). The A1 horizon is about 30-cm deep, reddish brown (5 YR 4/3 dry, 5 YR 3/3 moist), is hard, friable, sticky and plastic, with fine and very fine tubular and interstitial pores. The B2t, 30-65 cm is reddish brown (5 YR 4/4 dry, 5 YR 3/4 moist) with medium, subangular blocky structure, hard, friable, sticky and plastic with fine and very fine tubular and interstitial pores, with clay films lining ped surfaces. The B3t varies in depth, averaging about 75 cm, with similar properties to the B2t but with many thick clay films. The boundary between the B3t and the R horizon is fairly abrupt, but irregular and angular fragments of weathered parent material are common.

METHODS

Field Sampling

Effects of clearcutting were determined by comparison of adjoining uncut and clearcut areas. Soil moisture tubes (3.5 cm in diam) fitted with ceramic cups (Grover and Lamborn, 1970) were placed in triplicate on the same slope contour at the following depths in 1-ha plots in both areas: 8, 15, 23, and 31-cm. The tubes were brought to 50-cbar suction with a hand pump after sampling on 10 occasions during the rainy season (December 1974-May 1975). Solution volumes were measured on sampling, and 200 ml of solution was taken for chemical analysis. Rainfall, throughfall, and soil water contents were also monitored at this site following main precipitation events using methods described by McColl (1977).

The forest floor was sampled for chemical analysis in March 1975 from nine random points in the forest area within the vicinity of the soil solution samplers. Composite samples of the O1 and O2 layers were taken from areas of about 25 cm by 25 cm with a sharp-edged shovel. In both clearcut and forest areas depths of the forest floor were measured at 30 random points using a measuring stick, and bulk density measurements of surface soil were made at 25 random points.

Chemical Analyses

Solutions were stored in plastic bottles in the dark at 3°C prior to analysis for specific conductance, pH, Ca^{2+}, Mg^{2+}, K^+, Na^+, Fe^{2+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, NH_4^+, NO_3^-, $H_2PO_4^-$, SO_4^{2-}, Cl^-, and HCO_3^-. The metallic cations were determined by atomic absorption spectrophotometry (Isaac and Kerber, 1971), NH_4^+ by specific ion electrode, NO_3^- by the diphenylamine method (Ulrich, 1974) modified for water analysis, $H_2PO_4^-$ by the colorimetric method (Johnson and Ulrich, 1959), SO_4^{2-} by turbidimetry and Cl^- by titration (Environmental Protection Agency, 1974), alkalinity, assumed to be primarily HCO_3^- but also organic acids, by potentiometric titration (Rainwater and Thatcher, 1960). Specific conductance and pH measurements were standardized at 25°C (Rainwater and Thatcher, 1960).

Forest floor samples for chemical analysis were dried at 70°C for 48 hours, ground in a Wiley mill to pass a 20-mesh sieve, then 125-mg samples were digested in a mixture of nitric and perchloric acids. Cations were determined by atomic absorption spectrophotometry (Isaac and Kerber, 1971).

Statistical Analyses

Data was summarized and analyzed using Biomedical Computer Programs (Dixon, 1967) on file at the computer center, University of California, Berkeley. Calculations included means and standard errors, students' *t*-tests for differences between means, and simple correlation coefficients.

RESULTS AND DISCUSSION

Changes in Ion Concentrations

Mean concentrations of some major ions (K^+, Ca^{2+}, Mg^{2+}, NO_3^-, and HCO_3^-) in soil solutions from the clearcut were significantly lower than those in the forest at the 8-cm depth; lower concentrations for some ions also occurred for other depths (Table 2). There were also

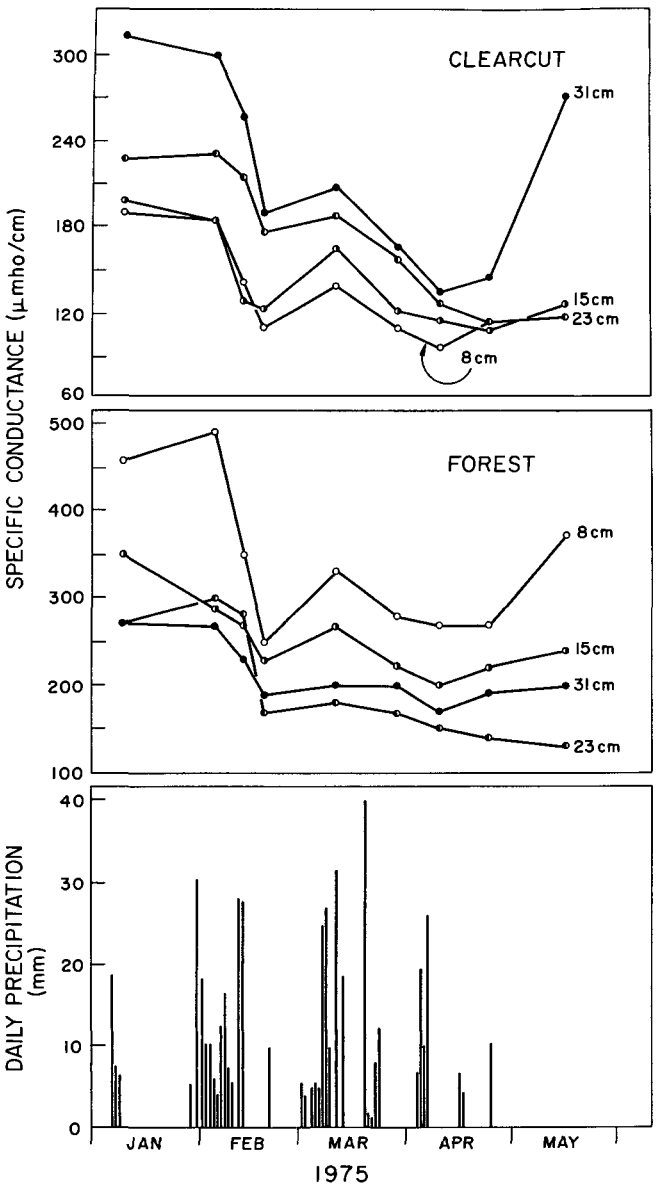

Fig. 1—Daily rainfall and changes over time of specific conductance of soil solutions from 8, 15, 23, and 31-cm depths in clearcut and uncut *E. globulus* forest sites, Berkeley hills, California.

significant decreases in specific conductance and pH due to clearcutting (Table 2). Sodium concentrations were the same at the 8-cm depth, but were significantly higher in the clearcut at lower depths (Table 2). Iron concentrations also increased at the 8-cm depth followng clearcutting; this result is discussed later with reference to Mn. Results for other ion species were less clear, with significant differences between forest and clearcut areas having less consistency with profile depth (Table 2). No NH_4^+ was detected in soil solution of either clearcut or forest areas. Clearcutting possibly increased the soluble organic-N fraction in solution, but transfer of this fraction and the source of NO_3^- detected in the soil solutions await future investigation.

Relative differences between ion concentrations at each depth were largely maintained throughout the sampling period as shown by values for specific conductance, used here as an index of total ion concentration (Fig. 1). In the forest, specific conductance was greatest at the 8-cm depth and lower at the 23-cm and the 31-cm depths due to nutrient uptake by the trees. In contrast, values generally increased with depth in the clearcut. Changes in concentration over time varied in the same general manner in both areas, and reflected the fluctuations in amount and distribution of rainfall (Fig. 1).

The notable decreases in concentrations of major ions due to clearcutting are inconsistent with results of other studies in which various increases in nutrient concentrations in drainage waters occurred following forest cutting (e.g., Fredriksen et al., 1975; Gessel and Cole, 1965; Likens et al., 1970).

Several reasons help explain the results. For example, the soil of this study was a clay-loam with a higher cation exchange capacity with 39.8 meq/100 g Ca^{2+} and 15.3 meq/100 g Mg^{2+} (Zinke, personal communication) than that of the soil developed from glacial outwash parent material in western Washington which had only 1.9 meq/100 g Ca^{2+} and 2.1 meq/100 g Mg^{2+} (Cole and Gessel, 1968; Gessel and Cole, 1965). The conditions at Hubbard Brook, New Hampshire were also quite different. Revegetation of the clearcut area there was inhibited by herbicides, and slash was left on the clearcut area, which resulted in excessive nutrient release with drainage water for many months (Likens et al., 1970). In the present study, most of the slash and some forest floor material was removed during logging, exposing mineral soil in many places and mixing litter with mineral soil which resulted in decreased bulk density of surface soil other than on skid-trails (Table 1). However, rapid growth of annual grasses prevented surface erosion. Thus nutrient release from decomposing slash and litter was minimal in the clearcut area.

In the present study, rainfall was limited to the period November through May. Thus nutrient leaching following clearcutting was also limited to this period, rather than over the whole year when increased temperatures, if accompanied by sufficient moisture, would have enhanced rates of decomposition and leaching.

Another important point is that nutrient release due to clearcutting is a product of both ion concentration in solution and the total volume of solution. Changes in ion concentrations and also total amounts, therefore, may result from volume changes, without variation in concentrations occurring. The dilution effect explains, but only in part, the lower ion concentrations observed in solutions from the 8- and 15-cm depths in the clearcut site. These points are discussed in detail later.

Changes in Relative Ionic Composition

To assess changes in relative ionic composition of major ions, concentrations were expressed as percentages of either total anions or total cations for each area (clearcut or forest) and each soil depth. Relative compositions of K^+, Ca^{2+}, NO_3^-, and HCO_3^- were lower in the clearcut, values for Mg^{2+} were unchanged, but values for Na^+, Cl^-, and SO_4^{2-} (at the 8- and 15-cm depths) were higher (Fig. 2).

These changes following clearcutting are attributed to ion inputs to the soil from rainwater without interception by

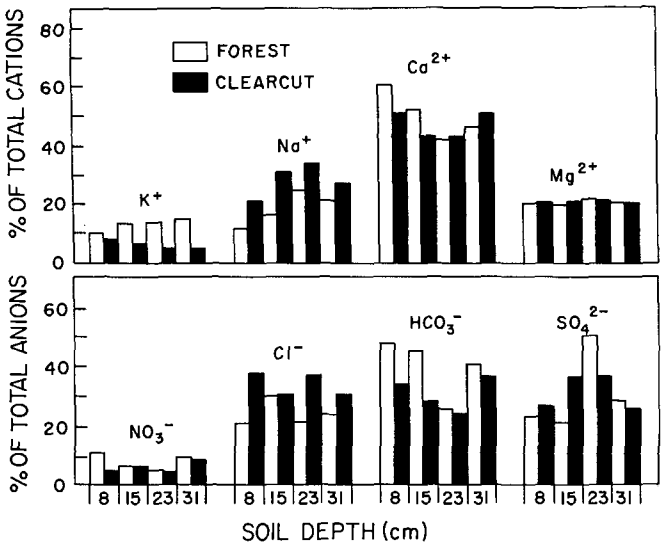

Fig. 2—Proportions of major ions in soil solutions from 8, 15, 23, and 31-cm depths, as percentages of either total cations or total anions, in clearcut and uncut *E. globulus* forest sites, Berkeley hills, California. Percentages are based on mean ion concentrations for the period December 1974-May 1975.

Table 3—Correlations between contiguous horizons for specific conductance, pH and ionic concentrations in soil solutions from clearcut and uncut *E. globulus* forest sites, Berkeley hills, California.

	Simple correlation coefficients and level of significance					
	Forest, cm depths			Clearcut, cm depths		
Ion	8 and 15	15 and 23	23 and 31	8 and 15	15 and 23	23 and 31
Specific conductance	0.85**	0.76**	0.89**	0.95***	0.84***	0.16
pH	0.64	0.26	0.46	0.92***	0.36	0.56*
K^+	0.48	0.14	0.45	−0.08	0.50	0.39
Na^+	0.66*	0.80**	0.93***	−0.10	−0.19	−0.48
Ca^{2+}	0.69*	0.44	0.83**	0.70*	0.69*	0.11
Mg^{2+}	0.84**	0.72**	0.92***	0.86**	0.71**	0.03
Cu^{2+}	0.64*	0.64*	0.75**	0.30	0.21	0.76**
Fe^{2+}	0.88***	0.47	0.60*	0.63*	0.85***	0.47
Mn^{2+}	0.97***	0.99***	0.92***	0.96***	0.97***	0.85***
Zn^{2+}	0.57	0.78**	0.25	0.49	0.70**	0.75**
NO_3^-	0.75**	0.55	0.63*	0.75**	0.45	0.60*
$H_2PO_4^-$	0.56	0.35	0.63*	0.78**	−0.31	−0.30
SO_4^{2-}	0.22	0.08	−0.16	0.05	−0.20	−0.22
Cl^-	0.86	0.73***	0.82***	0.33	0.57**	0.68**
HCO_3^-	0.74**	0.49	0.09	−0.19	0.49	0.37

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

the forest canopy or by passing through an intact litter layer. The average composition of rainwater on a molar basis during the study period, for major anions was: 49% SO_4^{2-}, 26% Cl^-, 18% HCO_3^-, 5% $H_2PO_4^-$, and 3% NO_3^-, and for major cations was: 48% Na^+, 19% Ca^{2+}, 10% H^+, 9% NH_4^+, 8% K^+, and 5% Mg^{2+} (McColl and Bush, 1977).[4] The relatively high proportions of SO_4^{2-}, Cl^- and Na^+ in rainwater resulted in increases in proportions of these ions in soil solutions in the clearcut. The significant decrease in pH from 7.0 to 6.2 at the 8-cm depth following clearcutting is also attributed to the input of acid rainwater, which had an average pH of 5.0 (calculated from mean H^+ concentration). Higher proportions of K^+, Ca^{2+}, NO_3^-, and HCO_3^- ions in soil solutions in the forest resulted from throughfall inputs (McColl and Bush, 1977)[4] and from decomposition and leaching of the intact litter layer.

The predominance of the HCO_3^- ion (i.e. alkalinity) in soil solutions in the forest supports the general results of McColl (1972, 1973a and b) in a study of ion transport in the soil of a Douglas-fir forest. The forest floor was shown to be the most biologically active component of the soil system, and it largely determined the ion characteristics of the solution in the mineral soil horizons below. The mobile HCO_3^- ion, a product of root respiration and biological decomposition and accompanied by organic acids, controlled the transport of cations in solution.

Correlations of Ion Concentrations Between and Within Soil Horizons

Significant correlations for ion concentrations between contiguous horizons were found for both clearcut and forest areas (Table 3). Fewer correlation coefficients were statistically significant for the clearcut area, due to disturbance of the litter and upper soil horizons in the logging operation.

Correlations between horizons for K^+ concentrations, however, were low and nonsignificant for both areas (Table 3) due to K^+-fixation by the 2:1-clay fraction (Black, 1968); clay content varied from 30% at the surface to 40% at lower depths (McColl, 1977).

Correlations of Mn concentrations between horizons were very high for both areas (Table 3). Correlations for Fe, although not as consistent were also high for surface horizons. Concentrations of Mn and Fe were also high in *E. globulus* litter (Table 1).

Details of the soil water regime at both clearcut and forest sites at various depths and over time have been reported in detail in an earlier report (McColl, 1977). During the study period volumetric soil water content exceeded 40% following rainfall. Soil porosity was 59% in the surface horizon (Author's unpublished data.) and probably much less with depth. The clayey soil apparently became anaerobic at these high water contents, at least during the movement of wetting fronts. When the surface soil was saturated, it would also seal off the lower profile, restricting loss of CO_2 and exchange of O_2 with the atmosphere, and cause increased cation leaching (Bloomfield 1965; Hallsworth, 1965; McColl and Cole, 1968). Such conditions also result in lowering of the Eh and in decreasing the pH, thus facilitating valence reductions in the oxides of Mn and Fe. Jenne (1968) points out that increases in water-soluble Mn (and Fe to a lesser extent) commonly occur with increasing clay content because of increased water retention and decreased aeration. Jenne (1968) also proposed that the hydrous oxides of Mn and Fe furnish the principal control on the fixation of heavy metals in soils, and that these oxides occurring as coatings enables them to exert chemical activity far out of proportion to their total concentrations.

Increases in the quantity of soil water following clearcut-

[4]J. G. McColl and D. Bush. 1977. Acid precipitation in the San Francisco Bay area (Ms. in preparation).

Table 4—Correlations within horizons for concentrations of minor ions and pH of soil solutions from clearcut and uncut *E. globulus* forest sites, Berkeley hills, California.

	Simple correlation coefficients and level of significance							
	Soil depth, cm							
	8		15		23		31	
	Fe^{2+}	Mn^{2+}	Fe^{2+}	Mn^{2+}	Fe^{2+}	Mn^{2+}	Fe^{2+}	Mn^{2+}
Forest:								
Mn^{2+}	0.99***	1.00	0.85**	1.00	0.83**	1.00	0.52	1.00
Cu^{2+}	0.91***	0.90***	0.40	0.59*	0.41	0.52	0.01	0.15
Zn^{2+}	0.82**	0.82**	0.21	0.32	0.44	0.73*	0.32	−0.11
pH	−0.60*	−0.63*	−0.83**	−0.88**	−0.12	−0.30	−0.01	−0.46
Clearcut:								
Mn^{2+}	0.56	1.00	0.87***	1.00	0.95***	1.00	−0.22	1.00
Cu^{2+}	0.39	−0.01	−0.09	0.03	0.74**	0.80**	0.84**	0.10
Zn^{2+}	0.81**	0.51	0.82**	0.68	0.80**	0.86**	0.55	0.52
pH	−0.67*	−0.91**	−0.89***	−0.89***	−0.54	−0.15	−0.15	−0.74**

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

ting may, therefore, result in increases in soluble Mn and Fe (Table 2) and associated heavy metals in the soil solution. High correlations also existed between Mn and Fe concentrations within horizons, and also for both Mn and Fe with Cu and Zn (Table 4) especially in the forest area where organic matter content was higher. There were also significant inverse correlations between solution pH and Mn and Fe concentrations (Table 4). Slight increases in $H_2PO_4^-$ concentrations after clearcutting (Table 2) are also symptomatic of anaerobic conditions (Black, 1968).

Correlations between other major ionic species were in most cases highly significant for both forest and clearcut areas for solutions at the various depths.

Changes in Total Ion Amounts

Clearcutting resulted in greater quantity of soil water at the study site (McColl, 1977) as well as altering ionic concentrations (Table 2). Both the volume of water and ionic concentrations of solutions sampled vary with changes in the suction gradient between the soil and the porous-cup devices used to extract soil solution (Hansen and Harris, 1975). The most appropriate use of such sampling devices is in comparative studies, such as the present one, where conditions were assumed to be the same except for the superimposed treatment. Here, differences between chemical characteristics of soil solutions in adjoining areas can be attributed to clearcutting. Differences in total ion amounts are best expressed as relative differences between control and treated areas. It is impossible to estimate total nutrient amounts moving in the soil profile in absolute amounts, or on an areal basis using the porous-cup sampling devices.

There was a significant relationship during the study period between soil matric suction (McColl, 1977), and volumes of solutions collected in the sampling tubes. For example, at the 15-cm depth the relationship was: $y = 429x^{-0.20}$ ($\alpha > 0.05$), where x is soil matric suction (cbar) and y is solution volume (ml). Thus the volume of solution collected between sampling dates can be used as an index of the total amount of solution in the soil. Solution volumes were multiplied by ionic concentrations to calculate ion amounts in clearcut and forest sites for each sampling period. The differences between total ion amount in the forest *(F)* and the clearcut *(C)* were expressed as a percentage of *F*, i.e., $(C - F)/(F) \times 100$. These percentages were then averaged for the whole study period (Table 5).

For all ions, except K^+, Mn^{2+}, Fe^{2+}, Zn^{2+}, and $H_2PO_4^-$ discussed earlier, clearcutting resulted in decreases in total ion amounts at the 8-cm and 15-cm depths and an increase at the 23-cm and 31-cm depths with only Cu^{2+} and SO_4^{2-} at the 31-cm depth as exceptions (Table 5). Thus clearcutting resulted in movement of ions from the upper soil profile and an accumulation at lower depths.

Another effect of clearcutting was, of course, removal of throughfall inputs to the soil, including washing off of impacted particulates and leaching of nutrients from tree crowns. These inputs are considerably larger than those in rainfall alone (between 2 and 13 times for different ions), and add the following quantities (kg ha^{-1} yr) to those of rainfall inputs: Na^+, 9.70; K^+, 9.67; Ca^{2+}, 6.32; Mg^{2+}, 3.89; NO_3^-, 1.19; SO_4^{2-}, 43.41; HCO_3^-, 6.16; Cl^-, 26.95; $H_2PO_4^-$, 0.02 (McColl and Bush, 1977).[4] Removal of these inputs also contributed to the lower ion amounts in soil solutions of the clearcut area.

CONCLUSIONS

1) Concentrations of K^+, Ca^{2+}, Mg^{2+}, NO_3^-, and HCO_3^-, pH and specific conductance of soil solutions decreased following clearcutting. Factors contributing

Table 5—Percentage change in total ion amounts in soil solutions due to clearcutting *E. globulus* forest, Berkeley hills, California.

	Soil depth, cm			
Ion	8	15	23	31
K^+	−78	−78	−53	−68
Na^+	−44	−4	141	64
Ca^{2+}	−78	−62	84	30
Mg^{2+}	−71	−49	80	22
Cu^{2+}	−73	−7	14	−34
Fe^{2+}	144	−10	141	147
Mn^{2+}	72	11	42	53
Zn^{2+}	−8	45	40	15
NO_3^-	−85	−34	107	18
$H_2PO_4^-$	40	85	18	96
SO_4^{2-}	−5	−9	10	−7
Cl^-	−4	−42	165	8
HCO_3^-	−70	−73	13	10

to these results were the high exchange capacity of the clay-loam soil, the short rainy season, the removal of slash and some litter, and the lack of ion inputs from throughfall in the clearcut.

2) Fluctuations of ion concentrations of soil solutions over time were related to the amount and distribution of rainfall.
3) Ion concentrations decreased with soil depth in the uncut forest, but increased with depth in the clearcut.
4) The proportion (expressed as a percentage of either total anions or total cations) of Na^+, Cl^-, SO_4^{2-} increased and the proportion of K^+, Ca^{2+}, NO_3^-, and HCO_3^- decreased in soil solutions in the clearcut, compared to those in the forest; the proportion of Mg^{2+} remained the same. No NH_4^+ was detected in soil solutions from either area. These changes resembled the relative ionic composition of the acid rain (mean pH 5.0) falling in the clearcut where most logging slash and litter had been removed. The high proportion of HCO_3^- in the soil solution in the forest was due to inputs from throughfall, root respiration, and decomposition of the intact forest floor.
5) Concentrations of many ions (except K^+) in the soil solution were correlated between contiguous soil horizons. Potassium was presumably fixed by clay which varied in amount with depth.
6) Anaerobic conditions, enhancing solubilities of Mn, Fe, Cu, and Zn and to some extent $H_2PO_4^-$ in the clearcut resulted from the high soil water content in the clay-loam soil, and from the sealing-off of the soil profile during the downward movement of wetting-fronts.
7) Total amounts of ions in the solution in the lower portion of the profile were greater in the clearcut due to increased quantity of soil water and subsequent increased leaching following clearcutting, rather than to increased ion concentrations of the soil solution.

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